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RESEARCH ARTICLE

Sustainable Inventory Model for Temperature-Dependent Deteriorating Products under Condition Monitoring

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Abstract

Cold-chain inventory processes that handle temperature-sensitive items are still facing issues because of deterioration losses, which have a direct impact on business profitability as well as sustainability. In contemporary logistics network, real-time condition monitoring systems are becoming more prevalent in operational practice; yet, their consequences for stock decision-making are often overlooked in optimization models. This study formulates an inventory model for temperature-dependent deteriorating products under price-sensitive demand, integrating the benefit of continuous monitoring by lowering actual deterioration rate. Optimum price and replenishing actions are derived by solving nonlinear optimization problem. Numerical analysis is performed under various temperature conditions to investigate the financial implications of monitoring-based deterioration reduction. The model is developed and evaluated in PYTHON, showing the reliability of the numerical findings. The results show that continuous monitoring drastically lowers deterioration-induced losses, leading to greater optimum replenishment periods and increased total profit across every temperature levels. This sustainable strategy highlights the importance of data-driven managerial oversight that enhances both resource utilization and cost effectiveness in cold- chain inventory operations.

Keywords: Inventory Model, Deteriorating Items, Cold-chain Operations, Temperature, Condition Monitoring, Sustainability.

Introduction

The effective control of temperature-dependent deteriorating commodities has drawn more interest because of the tremendous growth in cold chain operations for perishable items like food, medicines, and biological goods. Inventory decisions for these kinds of products are intrinsically complicated, since degradation rates are highly impacted by storage conditions and directly harm ecological and financial performance. To tackle these issues, various researchers have proposed a wide range of inventory models that explicitly integrate temperature-sensitive deterioration and pricing policies.

Yang et al. (2024) created an Economic Order Quantity model for temperature-dependent deteriorating products in cold chain processes, showing how distinct storage conditions affect spoilage rates and optimum ordering strategies. Kumar et al. (2025) developed an environmentally friendly inventory system for deteriorating items under controlled temperature circumstances by utilizing preservation techniques to reduce quality loss. Tayal et al. (2022) devised a decision approach that examines inventory effectiveness for degrading products while specifically considering temperature fluctuations in storage facilities. Priyamvada et al. (2022) analyzed the optimum inventory strategies for deteriorating goods by incorporating cost-sensitive investment in preservation methods, emphasizing the financial conflicts between deterioration mitigation and preservation costs. Sindhuja et al. (2023) constructed an inventory model with fluctuating demand using preservation systems, highlighting the importance of product quality in affecting demand behaviour.

Numerous researchers have also investigated price and supply decisions in perishable inventory models. Gu et al. (2024) modelled robotic pricing and replenishing techniques

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for perishable items with dynamic deterioration rates, demonstrating that fluctuating pricing substantially affect profitability. Macias-Lopez et al. (2021) created an inventory framework for perishable commodities with time, price and stock-dependent demand, taking into account shelf-life limits and nonlinear storage expenses. Noble et al. (2023) evaluated inventory handling strategies for food items with a fixed lifespan in a single-tier structure, offering insights into deterioration-based stock control. Sepehri et al. (2021) suggested a sustainable inventory-production model with defective quality and preserving techniques to show how quality enhancement efforts affect long-term economic efficiency.

Concurrently, researchers have thoroughly investigated continuous monitoring systems in perishable logistics as well as cold chains operations. da Costa et al. (2022) conducted an in-depth analysis of live tracking systems and their ability for lowering food loss and disposal throughout supply chains. Gillespie et al. (2023) validated the effectiveness of smart device-based real-time identification of anomalies in temperature-controlled transportation systems. Maheshwari et al. (2023) proposed an electronic dual-driven system for live scheduling and tracking of food supply chains, with a focus on increased operational transparency. Protopappas et al. (2025) looked at IoT tools to observe food supply chains, emphasizing their significance in improving traceability along with quality management. Aung et al. (2022) discussed the use of cold-chain monitoring devices and advanced sensors to ensure the product's quality throughout holding and transit.

Although the research mentioned above offers significant insights into temperature-dependent deterioration, pricing methods, and continuous monitoring technology, existing inventory models often consider deterioration rates as predetermined once the storage temperature has been set. Moreover, while real-time monitoring is extensively used in practice and proven to prevent spoilage, the financial benefit has not been analytically assessed within inventory models for temperature-dependent deteriorating products. To the best of our understanding, no research has explicitly addressed real-time monitoring technology as an endogenous deterioration-lowering method in a deterministic, price-sensitive inventory optimization paradigm.

To address this gap, this study suggests an economic production quantity model for temperature-dependent deteriorating items, where real-time monitoring is mathematically defined as a component that minimizes the effective rate of deterioration. Closed-form optimum criteria are developed, and numerical investigations are performed under various temperature conditions to highlight the financial advantages of incorporating real-time monitoring into cold chain inventory management.

Methodology:

This study develops a sustainable inventory model for temperature-dependent products that deteriorate under cold-chain environments. The model calculates total expenses based on system reliability and evaluate efficiency under two different approaches: Model 1 depicts the system without continuous monitoring whereas Model 2 includes real-time condition monitoring to mitigate the rate of deterioration.

Notations:

Notation	Description
$d(s)$	Rate of demand
δ	Rate of deterioration at temperature k
k	Product storage temperature
a	Ordering cost per cycle
b	Purchasing cost per unit item
c	Holding cost per unit item
l	Transportation cost per cycle
λ	Scale factor
γ	Pricing elasticity factor
ω	Monitoring efficiency factor
δ_r	Deterioration level under continuous monitoring
Q_T	Order quantity per cycle

Decision Variables:

T	Time duration per cycle
s	Selling price per unit item

Assumptions:

- Demand is price-dependent, then $d(s) = \lambda s^{-\gamma}$, where $\lambda \succ 0, \gamma \succ 1$.
- During storage, items decay instantly.
- Replenishment happens immediately, with no lead time.
- Shortages are strictly prohibited.
- The planning horizon is infinite.
- The rate of deterioration is temperature-dependent, where $\delta = 0.03e^{0.084k}$ and $0 \prec \delta \prec 1$

Model 1: Inventory model without real-time condition monitoring system

Let $I(t)$ represent the stock level at time t

$$\frac{dI(t)}{dt} = -\delta.I(t) - d(s),\ 0 \le t \le T \tag{1}$$

When $t = T$ we have $I(T) = 0$ (2)

Solving equation (1), we get

$$I(t) = \frac{d(s)}{\delta}(e^{\delta(T-t)} - 1) \tag{3}$$

Let $F(t)$ denote the inventory loss caused by decay in the period $[0,t]$.

$F(T)$, the difference between the inventory level at the final stage of the period with and without deterioration can be defined as

$$F(T)=\frac{d(s)}{\delta}(e^{\delta T}-1)-d(s).T \tag{4}$$

Then, the quantity ordered per cycle is

$$Q_T=F(T)+T.d(s)=\frac{d(s)}{\delta}(e^{\delta T}-1) \tag{5}$$

The total cost per cycle is comprised of the following components:

Ordering cost = a

Purchasing cost = $b.Q_T$

Holding cost = $c.\int_0^K I(t).dt=\frac{c.d(s)(e^{\delta T}-\delta T-1)}{\delta^2}$

Transportation cost = $l.Q_T$

Therefore, the total cost per cycle is

$$TC_1=a+b.Q_T+\frac{c.d(s)(e^{\delta T}-\delta T-1)}{\delta^2}+l.Q_T \tag{6}$$

The total cost per unit time is $TCU_1=\frac{TC_1}{T}$

$$TCU_1=\frac{a}{T}+\frac{b.d(s)(e^{\delta T}-1)}{\delta T}+\frac{c.d(s)(e^{\delta T}-\delta T-1)}{\delta^2 T}+\frac{l.d(s)(e^{\delta T}-1)}{\delta T} \tag{7}$$

By applying truncated Taylor series approximation $\delta T\ll 1$, we have

$$e^{\delta T}\approx 1+\delta T+\frac{\delta^2T^2}{2} \tag{8}$$

Therefore, equation (7) is reformulated as

$$TCU_1=\frac{a}{T}+\frac{b.d(s)\left(\delta T+\frac{\delta^2T^2}{2}\right)}{\delta T}+\frac{c.d(s)\left(\frac{\delta^2T^2}{2}\right)}{\delta^2 T}+\frac{l.d(s)\left(\delta T+\frac{\delta^2T^2}{2}\right)}{\delta T}$$

$$TCU_1=\frac{a}{T}+(b+l).d(s)+\frac{d(s)T}{2}[c+\delta(b+l)] \tag{9}$$

Differentiating equation (9) with respect to T and equating it to zero we get,

$$T=\sqrt{\frac{2a}{d(s)[c+\delta(b+l)]}} \tag{10}$$

The total revenue per unit time is

$$TRU_1=s.d(s) \tag{11}$$

Hence, the total profit per unit time is

$$TPU_1=TRU_1-TCU_1$$

$$TPU_1=s.ds-\left[\frac{a}{T}+(b+l).d(s)+\frac{d(s)T}{2}[c+\delta(b+l)]\right] \tag{12}$$

Model 2: Inventory model with real-time condition monitoring system

This model investigates the effect of information availability via real-time condition monitoring on replenishment decisions for temperature-dependent deteriorating products. In current cold chain processes, regular monitoring of the storage environment leads to early identification of temperature fluctuations and allows rapid corrective measures, such as adjusting freezing intensity or relocating goods inside warehouses. These steps do not completely prevent degradation, but they do slow the pace at which item quality drops gradually. From a modelling standpoint, this impact is expressed as a proportional decrease in the deterioration level of inventory items.

Thus, the effective level of deterioration under continuous monitoring is represented as

$$\delta_r=\delta(1-\omega)\text{, where } 0\le\omega\prec 1 \tag{13}$$

The greater ω value reflects better sensing, quicker reaction, and superior managerial oversight, resulting in less actual spoilage. The model enables a quantitative evaluation of the financial effect of continuous monitoring throughout the optimization process by incorporating this data-driven deterioration reduction directly into the mathematical framework.

Hence, total cost per unit time is

$$TCU_2=\frac{a}{T}+(b+l).d(s)+\frac{d(s)T}{2}[c+\delta_r(b+l)] \tag{14}$$

Differentiating equation (14) with respect to T and equating it to zero we get,

$$T=\sqrt{\frac{2a}{d(s)[c+\delta_r(b+l)]}} \tag{15}$$

Therefore, the total profit is

$$TPU_2=s.ds-\left[\frac{a}{T}+(b+l).d(s)+\frac{d(s)T}{2}[c+\delta_r(b+l)]\right] \tag{16}$$

Results

A numerical example is presented to demonstrate the practicality of the suggested model. The parameter values are taken from Yang et al. (2024) and industrial studies.

$a=450; b=40; c=1.5; l=2.5; \lambda=160,000,000;$
$\gamma=2.21; \omega=0.3$

Due to the nonlinear structure of the profit functions, computational optimization methods are used to find the optimum solutions under various temperature settings. The model is generated in PYTHON. The deterioration rate is assessed using the initial stored temperature and then modified to reflect the performance of the monitoring system. The efficiency of the model with and without real-time condition monitoring system are displayed in Table 1. and Table 2.

Table 1: Displays the efficiency of model 1

Temperature (°C)	*0 (°C)*	*7 (°C)*	*16 (°C)*
Deterioration rate	0.03	0.05401152	0.11503051
Selling price	78.06907	78.14508	78.30155
Demand rate	10513.36	10490.77	10444.5
Time duration	0.175638	0.150343	0.116136
Quantity rdered	1851.421	1583.637	1221.124
Total profit	368826.1	367958.0	366179.6

Table 2: Displays the efficiency of model 2

Temperature (°C)	*0 (°C)*	*7 (°C)*	*16 (°C)*
Deterioration rate	0.021	0.03780806	0.08052136
Selling price	78.03707	78.0951	78.21801
Demand rate	10522.89	10505.61	10469.16
Time duration	0.189072	0.166055	0.132156
Quantity ordered	1993.541	1749.993	1390.952
Total profit	369192.5	368528.5	367127.6

The numerical outcomes provide obvious structural details about how the system behaves under various temperature settings. As the stored temperature goes up, so does the rate of deterioration, directly reducing the demand fulfilment time. Thus, the optimum time duration and order quantity drop, highlighting the need for frequent replenishments to prevent product loss. The selling price becomes higher when temperature rises because the business modifies prices in order to offset greater losses due to deterioration.

The monitoring approach significantly decreases the deterioration rate, ensuring product availability and enhancing operational decision-making. This results in greater profit values than in the unmonitored circumstance at all temperature conditions. These findings indicate that monitoring devices can mitigate the adverse consequences of temperature excursion, promoting both operational effectiveness and financial sustainability.

Discussion

Prior studies on inventory models for temperature-dependent deteriorating products have mainly concentrated on pricing strategies, temperature-controlled methods and preservation investments to reduce deterioration and enhance system reliability (Priyamvada et al., 2022; Yang et al., 2024). Although these models adequately capture the effects of thermal conditions on degradation, they often use fixed deterioration factors and do not directly consider the function of data accessibility in reducing deterioration losses. Because of this, the dynamic impact of tracking methods is not entirely reflected in analytical inventory models.

In order to monitor the state of storage and react to quality fluctuations, organizations are now depending more and more on condition monitoring tools like temperature detectors and tracking appliances. Such monitoring increases availability and decreases spoilage, especially in cold-chain operations (Aung et. al, 2022; Gillespie et al., 2023; Protopappas et al., 2025). Nevertheless, despite their extensive industrial implementation, the financial impact of real-time condition monitoring system has seldom evaluated within profit-oriented inventory models.

To fill this gap, this research integrates condition monitoring into inventory model by estimating its impact on deterioration rate. This method enables the economic advantages of increased information accessibility to be examined without changing the fundamental framework of the inventory system. The numerical outcomes prove that reducing monitoring-related deterioration results in increased profitability. Therefore, this study reinforces the link between managing perishable products and analytical inventory models.

Conclusion

This study investigated the function of a real-time condition monitoring in enhancing the performance of an inventory operation for temperature-dependent degrading items. The model examined how upgraded condition transparency impacts optimum procurement, price, and profit decisions by incorporating monitoring-driven deterioration mitigation into an inventory system. The ideal solutions were derived mathematically, making sure the proposed framework is applicable in reality. The numerical findings across various temperature settings show that implementing condition tracking consistently maximizes overall profit, even after considering expenses related to monitoring. The enhancement is more obvious at higher temperatures, where deterioration consequences are more severe, emphasizing the financial benefit of information accessibility in handling perishable stocks. The results indicate that monitoring can improve both operational efficacy and sustainability. From a managerial point of view, the suggested model serves as a decision-making tool for enterprises that manage temperature-dependent items, enabling them to assess the economic advantages of real-time monitoring system. Further studies could broaden the model by including stochastic demand, temperature uncertainty, and multi-tier supply chains.

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